Aerodynamic study and design of Fixed Wing and Multi-copter Combination

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Abstract:- This project aims to design a hybrid drone with fixed wing for the stable cruising as well as multi-copters for the vertical take-off and landing (VTOL) operations. Drones are utilized for number of applications leading from transportation to the surveillance purposes. Some drones are popular for their stable operation, while other for optimum landing and takeoff. Therefore, numerical analysis was performed on propeller, landing gear as well as on whole structure of the drone. The observed result from CFD analysis show that the velocity distribution had maximum velocity of 40 m/s at the mid span of the drone. In addition, the maximum stress obtained was on the landing gear with approximate value of 185 MPa which is due to the weigh and payload of the drone. The final model was built after the analytical and numerical analysis in order to achieve sustainable and reliable prototype.

Keywords: — Angle of attack, CFD simulation, Design optimization, Drag force, Fixed wing, Lift force, Takeoff, VTOL

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1. Introduction

Drones are utilized for numerous applications such as agriculture, construction, defense, delivery, entertainment, photography, marketing, rescue, research, and medicine. In the development of drones, improvements take place every year that purely focus on the development of its control system that is capable enough to handle all types of maneuvers for system operations in a more systematic and practical way respectively to get a more sustainable and practical result [1]. The three main classifications of drones are fixed-wing drones, multirotor drones, single-rotor drones, and hybrid drones. Some drones are popular for their stable operation, while others are for optimum landing and takeoff. The study is based on the design of a hybrid drone that is efficient in terms of stable and optimized cruising, while also having the option of Vertical Take-Off and Landing (VTOL). Different analyses and simulations were conducted in order to check the feasibility and reliability of the modeled design [2, 3].

2. Background Research

Many researchers have performed study on the different categories of drone based on their design and performance. Fixed wings are much similar to normal flight in terms of its working, so it lacks the option of vertical takeoff or landing, and need proper run away. In the study of design optimization of fixed wing aircraft, [2] main focus was on performing optimization to minimize the takeoff and landing distance, in order to widen its applications. Different configurations of airfoil, tail, gears and motor placement were considered. Structural and aerodynamic analysis was performed in order to increase the lift and better airflow. Moreover, maneuver capability was achieved through this after that the whole design was analyzed. The author described that lift, drag and their co-efficient are also determined using this analysis, as, results obtained were much favorable after optimization [4].

Krishnaraj et al. [2] had performed the aerodynamic analysis of hybrid drone containing quad copters. Computational Fluid dynamics (CFD) had been utilized for the determination of flow dynamics. The major purpose of this is to determine the lift force, drag force, drag co-efficient and lift coefficient. Moreover, velocity contours, continuity equation, general transport equation, energy equation, *x*-momentum equation, and special transport equation were utilized in this analysis [2]. The authors concentrated on the wing, fuselage, tail, and frame of the drone. In the case of the cruise flight, there is no change in velocity with respect to time and no inclination when drone is on a cruise mode. Flow conditions taken were wind speed was 10 m/s, weight (1 kg), kinematic viscosity ($1.5x10^{-5}$ m^2/s), density of medium (air) was 1.225 kg/m^3 and chord length = 0.2 m. Using this, the Reynolds equation came out to be 133,333, and lift and drag coefficient was obtained. From this, minimum force to overcome in order for smooth operation comes out 0.45 N. From NACA library three airfoils design were selected one was symmetric (NACA 0012), and two were asymmetric (NACA 6409, and NACA 6412). Optimization was performed on three of them to determine the one with optimum C_L to C_d. From the three, NACA 6409 airfoil profile was optimal in terms of lift to drag coefficient which contributes in the overall thrust while cruising. Velocity contours were generated to determine the aerodynamic advantage of every wing [2].

Zayed Almehiri et al. [5] conducted the aerodynamic analysis for the design of multi-drone system, containing the fixed wing as well as multi copter. Main purpose of performing this analysis was to design the drone capable enough to fly within fly range of 50 km^2 and for around 1.5 hours (more than the conventional designs). ANSYS and XFLRS software were used for the optimization of the airfoil, in order to achieve the maximum lift over drag, *L/D*. Various analysis like equivalent strain, stress, factor of safety, deformation, drag and lift force were determined. In order to ensure the stability of the drone, SST-K omega was taken as the turbulence model in the ANSYS Fluent, as it provides accurate results in case of turbulence and flow separation. Model verification was done by varying the mesh intensity. After that, CFD was run at different angle of attack, varying between 0^o to 15^o, along the wind velocity at 14 m/s, and results for lift and drag were determined. Drone was used to measure the temperature of humans during pandemic COVID-19, without any physical touch. Vue Pro 336, 45° (thermal imaging camera) was installed in it. Continuous out-focus option in the camera enables one to measure the temperature even at varying altitudes or any vibrations during flight. Through this, the design optimization of hybrid drone was evaluated. Figure 1 shows the Landing Gear optimization for hybrid drone with factor of safety for the reliable takeoff and landing [5].

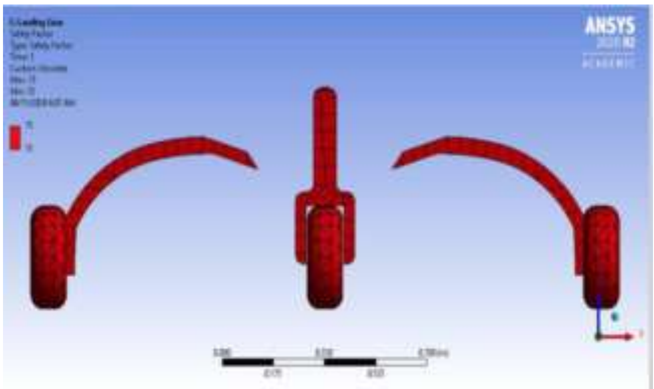

Figure 1: Landing gear safety factor *[5]*

In the propeller blade optimization, many researchers focused on enhancing the performance of drone by additions of ducts around its propellers [6]. From the study it was observed that by addition of ducts, power input has reduced by 29%, hence increase in the output efficiency. Krmela et al. concentrated on optimization of material of propeller blades. Three different materials i.e. PLA, PTEG and ABS were taken into consideration for the propeller blades and base. From the study, PTEG is the optimum material for both, because of its high stiffness that led to less stresses production [7].

The major critical components on drone are propeller and landing gear. Jigar conducted the optimization of landing gear to define its importance in drone's optimization and related applications. Fixed wing gear were analyzed under different landing conditions (i.e. impact loads), and for the all conditions, optimized design has factor of safety more than 2, confirming its reliability and stability [8].

3. Methodology

3.1 Conceptual Design

Three different components investigated deeply in this project; landing gear, propellers and the whole drone. Moreover, varies alternatives for each component studied and to become with the optimum alternative acquired for the design phase. Then the decision matrix took in consideration to show the highest weight of the alternatives. Table 1 and Fig. 2 illustrates the decision matrix and the varies alternatives shapes of the landing gear, respectively.

Table 1: Decision matrix of the landing gear (0-10)

decision matrix			
Criteria	Alt. 1	Alt. 2	Alt. 3
Cost	9	4	9
Manufacturing complexity	8	5	8
Ease of operation	5	7	10
Reliability	8	8	10
Total points	30	24	37

Figure 2: Landing gear alternatives

3.2 Set-up

Two different analysis applied in this project; Static Structural Analysis and Computation Fluid Dynamic (CFD) Analysis. For the CFD Analysis the different models are existing to solve the Reynolds Average Navier-Stokes Equation (RANS). Equation 1 shows the general equation of the Navier-Stokes equation [9].

$$\frac{d}{dt}\int_V \rho\phi\, dV \int_{\partial V} \rho\phi\,(\vec{u} - \vec{u_g})\,.\,d\vec{A} = \int_{\partial V} \Gamma\, \nabla\phi\,.\,d\vec{A} + \int_V S_\phi\, dV \quad (1)$$

where V is the volume, $\emptyset$ is general scalar, $\vec{u}$ is the velocity vector, $\vec{u_g}$ is the mesh velocity vector, Γ is the diffusion factor and S_ϕ is the source term of $\emptyset$. However, since the flow in the turbulence region a turbulence model is acquired to solve the steady state RANS equation. Table 2 shows more details about the CFD analysis parameters. The fluid that was used in the analysis was air. The properties of air are shown in Table 3.

Table 2: CFD Analysis details

Models	Method
Mesh type	Tetrahedron
Problem type	Steady state

Turbulence model	K–□ (SST)
Inlet boundary condition	Velocity inlet (32 m/s)
Outlet boundary condition	Outlet pressure (pressure gauge)
Working fluid	Air (1.225 kg/m^3)
Calculation method	Coupled

Table 3: Properties of air used in CFD

Properties	Air
Density, kg/m^3	1.184
Specific heat capacity, J/kg·K	1007
Thermal conductivity, W/m·K	0.02551
Dynamic viscosity, Pa·sec	1.8949E−5
Absorption coefficient, 1/m	0.49919, constant
Scattering phase function	Isotropic
Scattering coefficient, 1/m	0
Thermal Expansion Coefficient, 1/K	0.0033445

For the structural analysis, the boundary condition applied was to be fixed support at the landing gear while applying a vertical acceleration towards the ground as shown in Fig. 3. A fixed support was applied at the bottom and to include the weight of all components, gravitational acceleration was applied.

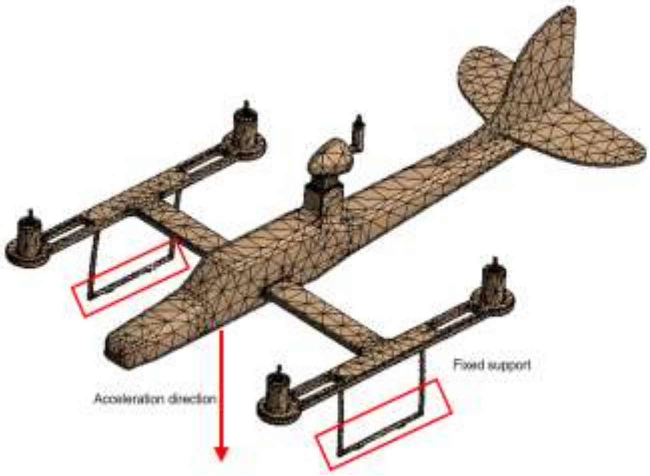

Figure 3: Structural boundary conditions

4. Result & Discussion

In the computational fluid dynamics (CFD) analysis, the contour plot of velocity at mid of the plane is represented in the Fig.4. From the plot, the maximum velocity is indicated by the red color in contour and the minimum velocity is shown by the blue color [10]. The maximum velocity in this case is 40.379 m/s and the minimum velocity is 0 m/s.

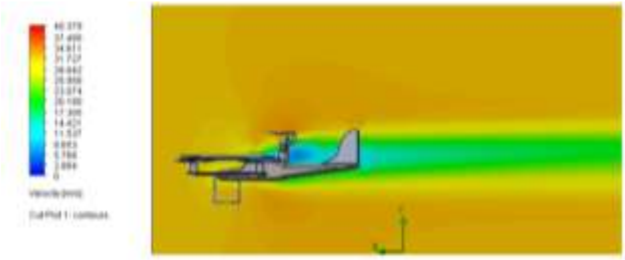

Figure 4: Velocity contour at mid of plane

The contour plot of velocity for CFD analysis at the wing of plane is shown in the Fig. 5. The greatest velocity is shown by the red color in the contour, while the minimum velocity is indicated by the blue color [11]. The greatest velocity is 38.6 m/s and the minimum velocity is 0 m/s. The red tint denotes maximum velocity locations. Increasing the angle of attack increases both lift and drag. If the angle of attack is too high (often approximately 17 degrees), the airflow across the upper surface of the aero foil becomes disconnected, resulting in a loss of lift, also known as a stalling effect.

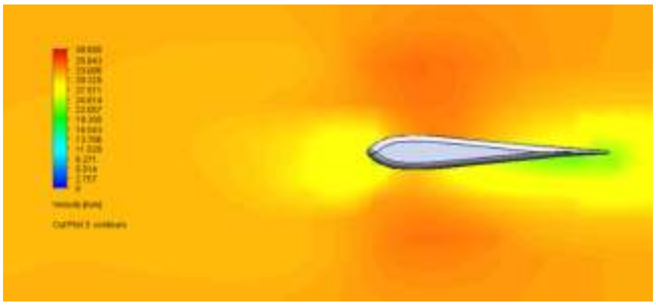

Figure 5: Velocity contour at tip of wing

It can be seen that region of low velocities shown in green color are present near the body of the plane. This is because of no slip condition. The no-slip condition for viscous fluids in fluid dynamics assumes that the fluid will have zero velocity relative to a solid boundary. The fluid velocity is equal to the solid velocity at all fluid–solid interfaces. The velocity contour from the front view is depicted in Fig. 6.

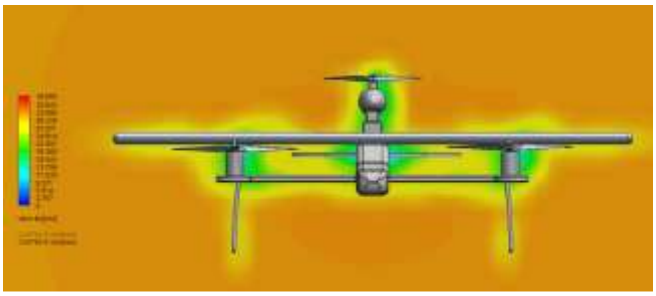

Figure 6: Velocity contour front view

The overall pressure contour plot on the surface of the drone for CFD analysis is shown in the image below (Fig. 7) where the greatest pressure is 102,336.19 Pa and the minimum pressure is 100,371.21 Pa.

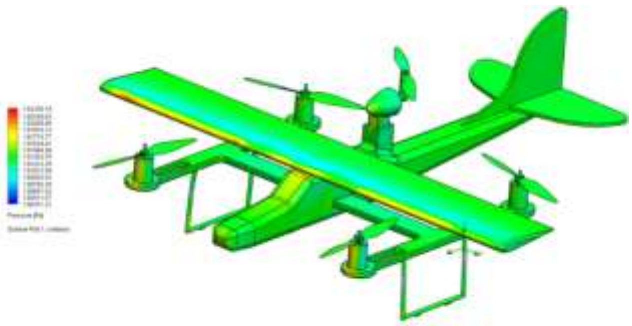

Figure 7: Pressure distribution

From the structural analysis, the von misses stresses contour map in Fig.8 shows that the maximum stress is 185 MPa which is the stand region on which the weight of the body acts when drone lands on the ground [7].

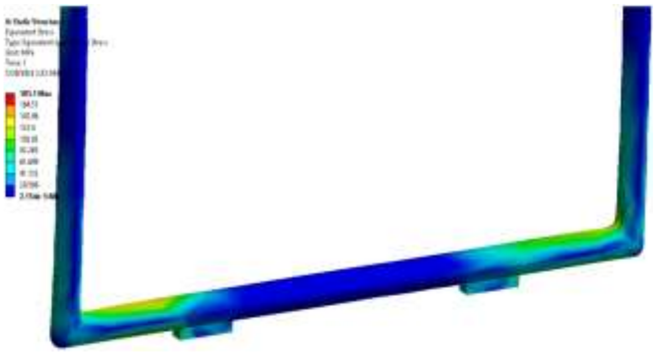

Figure 8: Stresses at base

The total deformations contour map is depicted in the Fig. 9 where red color in the contour indicates the maximum value of deformation that is 1.35 mm. The region with maximum deformation lies near the tail, and minimum deformation is on the stand, which are on the ground.

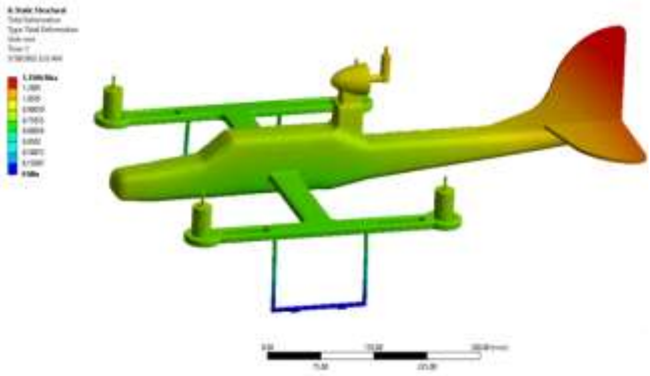

Figure 9: Total deformations

Figure 10 illustrates the equivalent strain contour map for structural study on the drone. Maximums strain is 0.0009. The region with the maximum strain is shown in the attached figure with red color, and this is the stand on which the weight of the body acts when the drone descends on the ground [8].

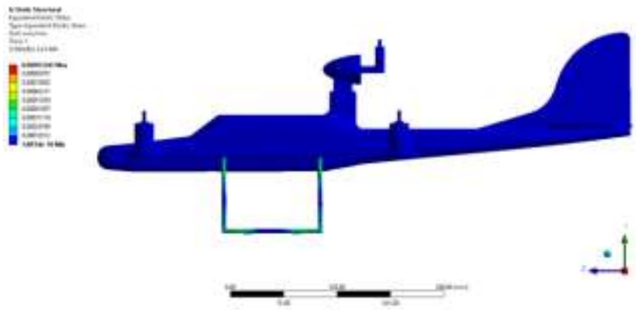

Figure 10: Strain in drone

5. Final Design

The final model of the drone was modeled in Fusion360 after the finalization of design and simulations in order to confirm its reliability and sustainability. Figure 11 and Table 4 represents the final design in CAD and real model with dimensions, respectively. The estimated price on manufacturing the drone is 1,600 USD. The price is including all the requirement on building the drone in Abu Dhabi University, at the laboratory of Mechanical Engineering Department.

Figure 11: Final Design; (a) CAD model; (b) Real prototype

Table 4: Final design dimensions

Components	Size in cm
Drone length	175
Drone width	230
Drone height	75

6. Conclusion

Drones are utilized for number of applications leading from transportation to the surveillance purposes. This project was successfully in design optimization of the hybrid drone. In this work, pressure and velocity contour, as well as their lift and drag are determined. Next, FEA analysis of the drone is performed in which velocity and pressure contour on the top of tip of wing and tail are determined, as it is the most critical part of drone. For this CFD analysis, maximum velocity comes out to be 38.6 m/s. increasing angle of attack will increase lift as well as drag, but at a certain limit, after which they will tend to decrease. Moreover, the maximum pressure comes out be 0.102336 MPa, which is present at the front side of fixed wing and propeller. Maximum value of stress is 185 MPa, which occur at the corners of the base. Maximum deformation value is 1.35 mm, which occurs at the back wings. Moreover, maximum strain (0.0009) is present on the base. Overall, its safety factor comes out to be 1.62, showing that the design is safe and acceptable. However, its safety can be improved by increasing the thickness of the stand, as it is the most critical region. The model manufactured after structural and CFD analysis in order to make sure the reliability as well as to test the model based on the simulation results obtained with overall cost of 1,600 USD.

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